

**SEARCH FOR EXTREMELY DEFORMED FISSION  
FRAGMENT IN  $^{28}\text{Si}+^{28}\text{Si}$  WITH EUROGAM PHASE II**

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## Abstract

A high-resolution study of fragment-fragment- $\gamma$  triple coincident measurements of the symmetric-mass fission exit-channel from the  $^{28}\text{Si}+^{28}\text{Si}$  reaction has been performed at the VIVITRON Tandem facility by using the EUROGAM Phase II  $\gamma$ -ray spectrometer. The bombarding energy  $E_{lab}(^{28}\text{Si}) = 111.6$  MeV has been chosen to populate a well known quasi-molecular resonance in  $^{56}\text{Ni}$ . Evidence is presented for a selective population of states in  $^{28}\text{Si}$  fragments arising from the symmetric-fission of the  $^{56}\text{Ni}$  compound nucleus. In the resonant region the enhanced population of the  $K^\pi = 3_1^-$  band of the  $^{28}\text{Si}$  nucleus, indicative of an oblate deformed shape, appears to play a significant role in the collision processes. The resonant behavior in the elastic and inelastic  $^{28}\text{Si}+^{28}\text{Si}$  exit-channels is found to be correlated to strong disalignment features of the di-nuclear oblate-oblate system with an equator-equator stable configuration.

## I. Introduction

In recent years, extensive efforts have been made in the study of the fusion-fission (FF) dynamics of very light di-nuclear systems [1–4] ( $40 \leq A_{cn} \leq 60$ ). Statistical decay processes [1,4] have been demonstrated to influence reaction channels that have been previously explored in terms of heavy-ion resonance mechanisms [5]. The FF mechanism is known to play a significant role at spins slightly above the grazing angular momentum; the nuclear configuration leading to the resonance behavior is only slightly more extended than that of the nuclear saddle point. According to the number of open channels (NOC) model [6], it has been shown that the coexistence of statistical fission from the  $^{56}\text{Ni}$  and the resonances arising from very deformed configurations of this composite system are well explained. The NOC model [7] predicts that the  $^{28}\text{Si}+^{28}\text{Si}$  collision has all the required features associated with surface transparency that are generally observed in much lighter “resonating” systems such as  $^{12}\text{C}+^{12}\text{C}$  and  $^{16}\text{O}+^{16}\text{O}$ .

It has been suggested that a coherent framework may exist which connects the topics of heavy-ion quasi-molecular resonances, superdeformation effects and fission shape isomerism [6–8]. In particular shell-stabilized, highly deformed configurations (as illustrated by the existence of “superdeformed” second minima in potential energy surfaces as calculated by the Nilsson-Strutinsky model shown in fig.1) in the  $^{56}\text{Ni}$  compound system have been conjectured [8] to explain the strong resonant behavior as observed at large angles for the  $^{28}\text{Si}+^{28}\text{Si}$  reaction [5]. Very narrow widths of about 150 keV high-spin resonances (see fig.2) are found to be well correlated in the elastic and inelastic decay channels of single and mutual excitations. This narrow and regular structure appears to correspond to a complex pattern of isolated high-spin resonances in the di-nuclear system with angular momenta, obtained from elastic scattering angular distributions [9], ranging from  $34\hbar$  to  $42\hbar$  following the grazing partial wave sequence.

This very striking quasi-molecular resonant structure can possibly be correlated to a

rather special subset of high-spin states stabilized against mixing into the more numerous compound nucleus states by some special symmetry [8]. As a matter of fact recent theoretical investigations have indicated that shell-stabilized “hyperdeformed” shapes may exist in the  $^{56}\text{Ni}$  nucleus with large angular momenta [10,11]. By the use of a molecular model proposed by Uegaki and Abe [12,13], a stable configuration of the di-nuclear system is found to be an equator-equator touching one, due to the oblate deformed shape of the  $^{28}\text{Si}$  nuclei [11]. In this report, we present for the first time experimental results using very powerful coincidence techniques which indicate the possible occurrence of a butterfly mode excitation responsible of the quasi-molecular resonant structure.

## II. Experimental Techniques

The aim of the experiment we have performed at the VIVITRON tandem facility of IReS Strasbourg with the EUROGAM Phase II multi-detector array was to search for highly deformed bands in the  $^{28}\text{Si}$  nucleus as produced in the  $^{28}\text{Si}+^{28}\text{Si}$  FF reaction.

A bombarding energy  $E_{lab}(^{28}\text{Si}) = 111.6$  MeV has been chosen to populate the well known  $38^+$  resonance [5,9,8] as shown in fig.2. The experiment has been carried out in triple coincidence modes (fragment-fragment- $\gamma$ ) with two fission fragments mass identified with two pairs of large-area position-sensitive Si(surface-barrier) detectors placed on either side of the beam axis by using standard kinematic coincidence techniques [14] and the  $\gamma$ -rays detected in EUROGAM Phase II multi-detector array. To establish the absolute normalization of the binary products yields, the elastic scattering data as measured by Betts [15] at a bombarding energy  $E_{lab}(^{28}\text{Si}) = 112$  MeV have been used. Energy and relative efficiency calibrations of EUROGAM Phase II were obtained with standard  $\gamma$ -ray sources and a AmBe source for the higher energy  $\gamma$ -ray region [16].

### III. Fragment-fragment coincidence data

Fig.3 shows the gated two-dimensional spectrum of the ejectile energy  $E_3$  as a function of the calculated excitation energy  $E_x$  for the  $^{28}\text{Si}+^{28}\text{Si}$  symmetric-fission exit-channel. The vertical band correspond to different excited states in the two  $^{28}\text{Si}$  fragments, whereas the regular concentrations of yields are due to strongly structured angular distributions.

The excitation-energy spectrum of the  $^{28}\text{Si}+^{28}\text{Si}$  symmetric-fission exit-channel, displayed in fig.4, exhibits a very striking and well structured behaviour up to high excitation energy ( $E_x \approx 15$  MeV). The low excitation-energy peaks correspond essentially to the elastic scattering and inelastic scattering to low lying states of  $^{28}\text{Si}$  (mainly the 1.78 MeV  $2^+$ , and 4.62 MeV  $4^+$  states), strong peaks are observed at much more negative Q-values and more likely arise from mutual scatterings. The states assignments are indicative since the higher  $E_x$  lying peaks are speculative although the locations of these peaks are consistent with mutual excitation of yrast states in both fragments as suggested previously [14]. The high selectivity in the final-state population will be discussed more in detail in the analysis of the  $\gamma$ -ray coincident results.

The angular distributions are extracted from the projections on the  $E_3$  axis with excitation energy gates as defined by the states of fig.4. The  $^{28}\text{Si}(^{28}\text{Si},^{28}\text{Si})^{28}\text{Si}$  identical particle exit-channels at  $E_{lab} = 111.6$  MeV are found to have at backward angles (between  $70^\circ \leq \theta_{c.m.} \leq 110^\circ$ ) strongly oscillatory angular distributions in the elastic, inelastic and mutual excitation channels as shown in fig.5 (points). The elastic cross sections observed in this angular region are from one to three orders of magnitude (near  $\theta_{c.m.} = 90^\circ$ ) larger than those obtained from optical-model calculations using standard strongly absorbing potential parameters which give a good account of the data forward of  $\theta_{c.m.} = 70^\circ$ . This behavior suggests the presence of a quite longer time-scale mechanism than the direct and multistep processes that dominate at more forward angles ( $\theta_{c.m.} \leq 70^\circ$ ). In this latter case the scattering processes have a characteristic dependence of the cross sections (with a steep and

smooth fall off beyond the grazing angle  $\theta_{c.m.} \approx 44^\circ$  as deduced from the elastic scattering [17]) under the influence of Coulomb repulsion with strong absorption for small impact parameters.

The present large-angle high-quality data, with good angular (position) resolution and high statistics, are well described by the curves of fig.5 as calculated by  $P_L^2(\cos\theta_{c.m.})$  shapes with  $L = 38\hbar$  in perfect agreement with the older data of Betts et al. [9]. The fact that the measured angular distributions correspond to shapes characterized by a single Legendre polynomial squared means that the resonant behavior is dominated by a unique and pure partial wave associated with the angular momentum value  $L = 38\hbar$ . This value can finally be considered as the spin of a well defined and isolated quasi-molecular resonance. It should be noticed that this value is greater than the critical angular momentum that can be extracted from the complete fusion data [17,18]  $L_{crit} \approx 35\hbar$  and lower than the grazing angular momentum  $L_{graz} \approx 38-40\hbar$  as obtained from a quarter point analysis of the elastic scattering [17]. The total cross section of the identical particle exit-channel which can be estimated from the excitation energy spectra is found to be around 10-12 mb, i.e. approximately 1% of the total complete fusion cross section [17,18]. FF calculations [1,4] do predict approximately 5-10 mb for the symmetric-mass fission cross section.

The fact that the angular momentum  $L = 38\hbar$  is dominant in these resonant channels means that the projection of the spin along the direction perpendicular to the reaction plane is  $m=0$ .

#### IV. Fragment-fragment- $\gamma$ coincidence data

In this section we will focus our analysis of the fragment-fragment- $\gamma$  coincidence data on the  $^{28}\text{Si}+^{28}\text{Si}$  symmetric-fission exit-channel as defined in the previous section. Doppler-shift corrections were applied to the  $\gamma$ -ray data of fig.6 on an event-by-event basis using the measured velocities of the detected  $^{28}\text{Si}$  fragments. Since it is not possible to know *a priori* which of the two fragments emits the detected  $\gamma$ -ray, both Doppler corrections were applied by using the method developed in Ref. [1,19]. In order to investigate the resonant effects on the feeding of the  $^{28}\text{Si}$  states and to search for highly deformed bands in  $^{28}\text{Si}$ , we have selected the  $73.2^\circ \leq \theta_{c.m.} \leq 105.6^\circ$  angular region where the angular distributions strongly oscillate as shown in fig.5. This region will be called in the following as the resonance region because strong absorption features are known to be less significant due to the Coulomb repulsion.

The feeding of  $^{28}\text{Si}$  states in the resonance region, which are presented in fig.7, indicates that the  $K^\pi = 3_1^-$  band is more strongly fed than the  $3_1^+$  band. The population of the 6.88 MeV collective  $3^-$  state, which was not apparent in the fragment-fragment coincident data as presented in fig.4, is quite strong. This is an indication that  $^{28}\text{Si}$  has an *oblate deformed* shape when the resonant features are present.

As already mentionned in a study of the  $^{24}\text{Mg}(^{32}\text{S}, ^{28}\text{Si})^{28}\text{Si}$  reaction [19], the population of the second excited band  $K^\pi = 0^+$  appears to be significantly well populated. Statistical-model calculations [1,19] are in progress in order to check whether the role of this highly deformed prolate band in  $^{28}\text{Si}$  is of importance in the resonant structure.

One of the more particularly interesting feature in the ground state  $K^\pi = 0_1^+$  band is that the mutually excited states are more intensily fed than the singly excited states ( $0_1^+$ ,  $0_1^+$ ), ( $2_1^+$ ,  $0_1^+$ ), and ( $4_1^+$ ,  $0_1^+$ ) and the relative ratios between them are equal to 12 %. This high degree of selectivity in the population of mutually excited yrast states in both  $^{28}\text{Si}$  fragments definitively confirms the early findings of Betts et al. [14].



The complexity of the higher energy structures apparent in fig.4 obtained with the particle data makes it very difficult to assign specific mutual excitations to the structures observed at energy above  $\approx 6.5$  MeV. This can be however mostly resolved by the  $\gamma$ -ray data as shown by the two examples displayed in fig.8. The tentative spin assignments of the mutual yrast states as populated by the  $^{28}\text{Si}+^{28}\text{Si}$  symmetric-fission exit-channels with a very high degree of selectivity are more firmly identified by the fragment-fragment- $\gamma$  data. The particle spectra of fig.8 have been obtained by gating on  $\gamma$ -rays of the  $2_{1779}^+ \rightarrow 0_{gs}^+$  and  $4_{4617}^+ \rightarrow 2_{1779}^+$  transitions respectively. It is evident that the populations of the mutual excitations are dominant. However contributions from single excitation, such as the  $4^+$  state at 4.617 MeV which appears as a small shoulder on the  $(2^+, 2^+)$  peak [14,19] of the “inclusive” spectrum, are also present. This may partly contradict the early suggestion that the resonant yields result primarily from excitations of the yrast levels.

We have been able to construct other “coincident” spectra obtained with gates on the weaker  $3_{6276}^+ \rightarrow 2_{1779}^+$ ,  $4_{6888}^+ \rightarrow 2_{1779}^+$  and  $3_{6276}^+ \rightarrow 0_{gs}^+$   $\gamma$ -ray transitions. They all show that non-negligible contributions in the so-called  $(2^+, 2^+)$  and  $(4^+, 2^+)$  peaks of fig.4 arise also from the  $K^\pi = 3_1^-$  and  $3_1^+$  respectively.

Spin-alignment estimations of the low-lying excitation states (single inelastic  $2^+$  and mutual inelastic  $(2^+, 2^+)$  exit-channels) have been deduced by measuring their particle- $\gamma$  angular correlations with EUROGAM Phase II. Three quantization axes have been defined as follows:

- a) the first axis corresponds to the beam axis,
- b) the direction normal to the reaction plane represents the second axis,
- c) and finally the molecular axis is parallel to the relative vector which connects the two centers of the out-going binary fragments.

The same features are found for the two exit channels. In fig.9 the results of the  $\gamma$ -ray angular correlations for the mutual excitation exit-channel are shown because of its symmetry. The minima observed in a) and b) at  $90^\circ$  imply that the intrinsic spin vectors of the  $2^+$  states lie in the reaction plane and cannot be coupled with the relative orbital

angular momentum and the value of the total angular momentum remain  $J=38\hbar$  for the two exit channels in agreement with fig.5. The maximum around  $90^\circ$  in c) means that the  $^{28}\text{Si}$  spin vectors are lying in the reaction plane with opposite directions. The condition that the  $m=0$  configuration is the dominant mode of the collision in the  $^{28}\text{Si}+^{28}\text{Si}$  inelastic and mutual reactions fulfills the classical rolling limit which demands parallel intrinsic spins pointing in opposite directions. It can be pointed out that this condition along with the strong population of the  $3^-$  oblate deformed band can be relevant for the formation of a molecular di-nuclear complex with two pancake-like  $^{28}\text{Si}$  nuclei touching each other edge to edge so that the spin vectors of the fragments are in the pancakes' plane.

The weak coupling evidenced in the present work for the  $^{28}\text{Si}+^{28}\text{Si}$  system might be found to be in apparent contradiction with previous spin alignment measurements as performed for the  $^{24}\text{Mg}+^{24}\text{Mg}$  system [20–22]. However preliminary calculations [23] with the molecular model developed by Uegaki and Abe [11–13] do predict an oblate-oblate system with an equator-equator stable configuration (butterfly mode) for the studied reaction, whereas the resonance-like structure observed for  $^{24}\text{Mg}+^{24}\text{Mg}$  appears to be linked to a prolate-prolate system in a pole-pole configuration (anti-butterfly mode). In the case of collisions between two oblate deformed nuclei, there is some hints that the equator-equator orientation is the most important one for molecular resonances [24]. The observed mismatch of the spin vectors in  $^{28}\text{Si}+^{28}\text{Si}$  with the orbital angular momentum might be discussed [23] as a candidate of a butterfly mode excitation where the intrinsic spins of the two interacting nuclei couple to zero.

## V. Conclusions and Perspectives

The resonant behavior of the  $^{28}\text{Si}+^{28}\text{Si}$  reaction at  $E_{lab} = 111.6$  MeV is clearly confirmed by the present fragment-fragment coincidence data for the elastic and inelastic decay channels of single and mutual excitations. From the analysis of the particle angular distributions of these channels it can be concluded that :

- 1) the  $J^\pi=38^+$  resonance is now well defined,
- 2) the spin vectors of the  $^{28}\text{Si}$  fragments do not couple with the orbital angular momentum:  $m=0$ .

The fragment-fragment- $\gamma$  coincident data demonstrate that for the  $^{28}\text{Si}$  exit fragments :

- 1) the mutually excited states are the more strongly populated,
- 2) the population of the highly deformed prolate  $K^\pi = 0_3^+$  band is enhanced,
- 3) the  $K^\pi = 3_1^-$  band is strongly fed indicative of an *oblate* deformed shape for the fragments,
- 4) the  $^{28}\text{Si}$  spin vectors are lying in the reaction plane in opposite directions.

Qualitative arguments are in favor of the calculations of the molecular model of Uegaki and Abe [23] which predict a butterfly mode excitation for the  $^{28}\text{Si}+^{28}\text{Si}$  system, while an anti-butterfly motion is induced in the  $^{24}\text{Mg}+^{24}\text{Mg}$  collision. A statistical-model calculation [1] is in progress to describe both the structures observed at high excitation energy in the fission Q-value spectra and the population pattern of states in the  $^{28}\text{Si}$  fission fragments. This will suggest that these states may also reflect nuclear structure effects at the point of fission.

Similar studies are underway in the analysis of the  $^{28}\text{Si}(^{28}\text{Si}, ^{24}\text{Mg})^{32}\text{S}$  and  $^{28}\text{Si}(^{28}\text{Si}, \alpha\alpha)^{48}\text{Cr}$  exit-channels. This work call for experiments with EUROBALL and/or GAMMASPHERE to measure precise excitation functions of the  $^{24}\text{Mg}+^{24}\text{Mg}$  reaction which will also help in developing the differences and possible relationships between the heavy-ion resonance and compound-nucleus fission processes in light systems.

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## FIGURES

FIGURE 1 : Cranking Nilsson-Strutinsky calculations of potential energy surfaces for  $^{56}\text{Ni}$  at high spin  $I = 40\hbar$  shown plotted as a function of deformation  $\beta$  and mass-asymmetry  $M_r = M/56$  where  $M$  is the mass of one of the fragment (figure taken from [8]).

FIGURE 2 : Angle-integrated yields of the  $^{28}\text{Si}+^{28}\text{Si}$  elastic scattering,  $2^+$ , mutual  $2^+$ , and mutual  $(4^+, 2^+)$  excitations measured as a function of  $E_{c.m.}$  in 100 keV steps (figure taken from [5]). The top part of the figure shows in the total yield of the  $^{28}\text{Si}+^{28}\text{Si}$  exit-channel that many of the resonant structures of width 100-200 keV are well correlated.

FIGURE 3 : Ejectile energy  $E_3$  versus excitation energy  $E_x$  two-dimensional plot of the  $^{28}\text{Si}+^{28}\text{Si}$  symmetric-fission exit-channel.

FIGURE 4 : Excitation energy  $E_x$  spectrum for the  $^{28}\text{Si}+^{28}\text{Si}$  exit channel measured at large angles. Tentative assignments of the resolved and non-resolved peaks are indicated.

FIGURE 5 : Angular distributions of the elastic, inelastic  $2_1^+$  and mutual  $(2_1^+, 2_1^+)$ ,  $(4_1^+, 0_1^+)$  excitation channels. The solid lines are  $[P_L(\cos\theta)]^2$  shapes for  $L = 38\hbar$ .

FIGURE 6 :  $\gamma$ -ray spectrum in coincidence with the  $^{28}\text{Si}+^{28}\text{Si}$  symmetric-fission exit-channel.

FIGURE 7 : Measured feedings for states in  $^{28}\text{Si}$  populated in the resonance region.

FIGURE 8 : Excitation-energy spectra of the  $^{28}\text{Si}+^{28}\text{Si}$  exit-channel as gated by the  $2_1^+ \rightarrow \text{gs}$  and  $4_1^+ \rightarrow 2_1^+$   $\gamma$ -ray transitions.

FIGURE 9 :  $\gamma$ -ray angular correlations of the  $(2_1^+, 2_1^+)$  states of the  $^{28}\text{Si}+^{28}\text{Si}$  exit-channel for 3 different quantization axes.